



**IMPROVEMENT OF ADVANCING FRONT MESH METHOD IN TRIANGLE
HOLE FILLING**

By

NOOREHAN BINTI AWANG

**Thesis Submitted to the School of Graduate Studies, Universiti Putra
Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of
Philosophy**

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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Mesh-based or triangulated prototypes are widely used to represent objects in many modelling and computer-aided engineering applications. In certain cases, there is a possibility of missing points when scanning devices fail to enter certain regions; and those area captured as a hole in the scanning process. These holes need to be filled in order to develop an error-free triangulated prototype. The Advancing Front Mesh method is used to fill a triangle to overcome this problem. This method iteratively meshes a hole's area by inserting new triangles and nodes at the hole's boundary, then moves to the inside of the area until it is closed. However, problems occur when finding new points using this method. In this research, an improved Advancing Front Mesh method is proposed to solve the problem of filling holes when encounter three intersection problem for the triangular mesh. The first problem is that when a new generated point is unconnected to any active point, using the usual threshold circle. Thus the intersection point was calculated between the threshold circle to any line segment in a triangle in order to check for nearest active point. Secondly, the triangle created overlaps other triangles; the circumcircle surrounded all the starting points along with the new points was used to check for any extra active point. Then the magnitude was calculated between previous new point to the new active point to identify the correct points. Thirdly, when the new generated point is close to the hole's boundary, the threshold radius have been enlarged in order to find the new point. Then the bisection point was calculated if there is no active point in the enlarged radius. The first validation is carried out using the interpolating surface of the test data with three familiar bivariate functions. Meanwhile, the second "visual similarity" validation is carried out using a questionnaire to compare the experimental outcome with the original figure. The results of this research contribute to the method of satisfying an object's visualization and provides an enhanced method of AFM for filling a hole in triangular mesh.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENAMBAHBAIKAN KAEDAH JARINGAN DEPAN DALAM PENGISIAN LUBANG SEGITIGA

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Prototaip berasaskan jejaring atau triangulasi digunakan secara meluas untuk mewakili objek dalam banyak pemodelan dan aplikasi kejuruteraan berbantuan komputer. Dalam kes tertentu, terdapat kemungkinan titik hilang apabila peranti pengimbasan gagal memasuki kawasan tertentu; dan kawasan tersebut ditangkap sebagai lubang dalam proses pengimbasan. Lubang-lubang ini perlu diisi untuk membangunkan prototaip triangulasi bebas ralat. Kaedah Advancing Front Mesh digunakan untuk mengisi segitiga bagi mengatasi masalah ini. Kaedah ini secara berulang menyatukan kawasan lubang dengan memasukkan segitiga dan nod baharu pada sempadan lubang, kemudian bergerak ke bahagian dalam kawasan itu sehingga ia ditutup. Walau bagaimanapun, masalah berlaku apabila mencari titik baharu menggunakan kaedah ini. Dalam penyelidikan ini, kaedah jaringan hadapan yang ditambah baik dicadangkan untuk menyelesaikan masalah mengisi lubang apabila menghadapi masalah tiga persimpangan bagi jaringan segi tiga. Masalah pertama ialah apabila titik terjana baharu tidak disambungkan ke mana-mana titik aktif, menggunakan bulatan ambang biasa. Oleh itu, titik persilangan dikira antara bulatan ambang ke mana-mana segmen garisan dalam segi tiga untuk menyemak titik aktif yang terdekat. Kedua, segitiga yang dicipta bertindih dengan segitiga lain; bulatan mengelilingi semua titik permulaan bersama-sama dengan titik baharu digunakan untuk memeriksa sebarang titik aktif tambahan. Kemudian magnitud dikira antara titik baru sebelum ini ke titik aktif baru untuk mengenal pasti titik yang betul. Ketiga, apabila titik yang dijana baharu hampir dengan sempadan lubang, jejari ambang telah diperbesarkan untuk mencari titik baharu. Kemudian titik dua belah dikira jika tiada titik aktif dalam jejari yang diperbesarkan. Pengesahan pertama dijalankan menggunakan permukaan interpolasi data ujian dengan tiga fungsi bivariat biasa. Sementara itu, pengesahan "persamaan visual" kedua dijalankan menggunakan soal selidik untuk membandingkan hasil eksperimen dengan angka asal. Hasil penyelidikan ini menyumbang kepada kaedah memuaskan visualisasi objek dan menyediakan kaedah AFM yang dipertingkatkan untuk mengisi lubang dalam jaringan segi tiga.

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LIST OF ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
AFM	Advancing Front Mesh
CAD	Computer Aided Design
CAGD	Computer Aided Geometric Design
CMM	Coordinate Measurement Machine
CNC	Computer Numerical Control
DT	Delaunay Triangulation
EAFM	Enhanced Advancing Front Mesh
FIS	Fuzzy Inference System
LBF	Loopy Belief Propagation
MAFM	Modified Advancing Front Mesh
MC	Marching Cube
MRF	Markov Random Fields
PDE	Partial Differential Equation
RBF	Radial Basis Function
UAV	Unmanned Aerial Vehicles

CHAPTER 1

INTRODUCTION

1.1 Background of research

Reverse engineering is a model that transforms the existing product model or physical model into an engineering design model or conceptual model. With the development and application of computer technology especially the theories and techniques of computer aided geometric design, reverse engineering has become an important means to obtain three-dimensional model. Reverse engineering including data acquisition, data processing and surface reconstruction. Undoubtedly, the triangle mesh model has become the popular representation for 3D geometry modelling. It has been widely applied in the fields of Computer Graphics and CAD.

Three dimensional (3D) optical scanning devices can be used to capture the surface model of damaged parts in the form of a 3D point cloud with the use of computer vision and digital image processing technology. The measured 3D point cloud is frequently incomplete, resulting in numerous holes after the point cloud triangulation, due to the self-contained constraints of 3D scanning technologies and the occlusion between the physical item and the utilized scanner. This limitation caused those certain materials cannot be digitized. Some parts of the object may be missing or some local data of the mesh model may be lost due to the limitation of the quality of the scanning equipment.

The presence of holes in the mesh reduces the performance of downstream mesh processing algorithms, such as mesh alignment and Boolean operations, potentially leading to processing failure. Incomplete triangular meshes, on the other hand, may result in poor visualization effects. These holes influence many mesh operations and a mesh model with holes cannot be directly utilized by applications. Consequently, we have to fill and repair them in advance to obtain a whole mesh model of the object.

1.2 Problem statement

In the disciplines of mechanical manufacturing, emergency rescuing, biomedical engineering, and other fields, additive manufacturing repair has been widely employed to extend the lifespan of damaged parts as a typical cost-saving, digital, and intelligent manufacturing approach. However, with the rapid advancement of printing and scanning technologies, traditional manual repair is becoming increasingly time-consuming and labor-intensive, as well as producing uneven

quality. It is critical to have a system that can automatically fix damaged parts (Tabib et al., 2020).

3D scanning devices can employ either 'object in touch' (contact) or other approaches, where touching is not present (non-contact). Because of their high scanning speed, real-time applications, high precision, etc., non-contact methods are deemed more useful. As most 3D objects have complex geometries, contact methods are less required than non-contact techniques. New techniques to digitalize 3D objects include non-contact laser scanning, which allow 3D Computer Aided Design (CAD) frameworks to be created for objects with highly complex surfaces. The results of optical flow were used in this research for implementation. Optical flow was used to detect object movement between set of images where the displacement is able to provide information about an object relative to the observer's distance. Optical flow can be used to evaluate the depth value of that point and 3D point of the object can be achieved if a successful feature tracker is able to identify the matching feature point in the subsequent image or frame (Beng, 2015).

This approach exposes a missing point that creates a void in the region where the paint is white, shiny and glossy. The presence of undesired holes impacts the model's visualization, and can lead to unexpected results for the application; such as segmentation, rapid prototyping, and analysis of finite elements. A technique known as the Advancing Front Mesh (AFM) method was used to patch a triangle in a hole by adding new elements and nodes at the boundaries (referred to as the front) of an area; thus, iteratively meshing the area. One of the advantages of AFM is that the creation of a new triangle is co-instantaneous with the generation of a new node. The front then travels to the inside of the region until it closes. This benefits the ability to regulate the element's size and shape by changing the position of the node (Zhao, 2007; Agarwal and Agrawal, 2019; Feng, 2020).

However, there is a situation where conflict arises in the filling of hole and the AFM approach needs to be strengthened to solve problems with holes. If the original method cannot find the new point, the approach must be changed to address this issue. Furthermore, several AFM system implementations exist in handling triangle overlapping problems and discovering new points near the boundary of holes.

Problem of 3D object with missing holes on triangular mesh leading to the following **PROBLEM STATEMENT** for this research:

- a) no existing active point inside the identified threshold circle, thus there is a need to approximate and locate the position of a new point.
- b) approximation point created overlaps another triangular patches therefore the approximate point needs to reposition.

- c) point falls near the boundary of holes and not connected to any active points, thus to avoid skinny triangle the approximate point need to reposition.

1.3 Objective of research

The main aim of this work is to establish a procedure to approximate triangular patches into a hole. To achieve this aim, these are the objective that needs to fulfill:

- a) To introduce a new method on how to locate the approximation point when they are **no active point inside the threshold circle**.
- b) To propose a new approach on how to select candidate for approximate point when **the point created overlaps another triangle**.
- c) To construct a new algorithm **to avoid skinny triangle**.

1.4 Scope and limitation of research

Point cloud has become one of the most significant data formats for 3D representation. The general issues in point cloud distribution are irregularity, unstructured, and unorderness grid make the object difficult to model. The object chosen as a scope in this research was having irregularity characteristic as in research by Bello et al. (2020).

Irregularity: Point cloud data is irregular, meaning, the points are not evenly sampled across the different regions of an object/scene, so some regions could have dense points while others sparse points.

The scope of the study are four optical flow subject data, which **cover front and back views**. This gives a total of **8 subjects** under consideration for this research. The data points were obtained from optical flow research by (Beng, 2015). The data points can be divided into three types of holes, the normal holes, the overlap triangle hole and the holes near the boundary. Limitation of the data is only to the object which already have a presence of holes due to the scanning process. Thus, the data point was enough to use to solve the hole filling problems on triangle mesh. Furthermore, **the 36 test data points** Whelan T. (1986); Renka and Cline (1984) was used throughout each chapter for validation process.

MATLAB R2016a software was used to program all the techniques and display of figures in this research. The device use was Acer Laptop with processor of Intel(R) Core(TM) i3-8145U, CPU @ 2.10GHz 2.30 GHz, Installed RA 4.00 GB and system type of 64-bit operating system, x64-based processor.

1.5 Significance of research

The problem of missing point was due to an error during scanning and it weakening of both the visual effects of a 3D model and its post-processing performance. The three contribution listed in this study able to enhance the method of advancing front mesh method in solving different type of problems during holes filling. Thus, the process of hole filling will be faster and able to produce better 3D visualization result.

1.6 Thesis organization

The thesis is composed of seven chapters including Chapter 1 which mentioned as the introductory chapter. It begins with a background of research and applications analysis. In addition, the problem statement, research objective, scope and limitation of research and the significance of research are explained in this section.

Chapter 2 explains the previous and associated work on the 3D scanning devices, pre-processing technique, the holes filling, AFM-based hole filling techniques and smooth surface reconstruction.

Chapter 3 describes the research methodology and research framework, data acquisition, experiment subject, advancing front mesh used in the research and smooth surface reconstruction which used in validation method.

Chapter 4 describes the all the proposed method of enhanced AFM method. The chapter begins with preprocessing of the proposed algorithm technique and the process of finding holes by AFM method. The proposed method was explained in subtopic 4.3, 4.4 and 4.5. Each subtopic begins with an introduction, the suggested algorithm approach, implementation, findings and discussion and triangle outcome analysis.

Chapter 5 resolved the result and discussion chapter which explained on three validation method. Firstly, validation was the skewness of triangle mesh was calculated and compared with the result from previous researcher on the same method. Secondly the validation was using the test data where all the three problem was encounter. Third validation was visual evaluation via a questionnaire form which was known as a subjective visual similarity assessment.

Finally, in Chapter 6, this final chapter concludes the study, highlights the contributions and also provides an overall review of the proposed approach and recommends suggestions for future work.

REFERENCES

- Abal Abas, Z., Salleh, S., and Manan, Z. (2013). Extended advancing front technique for the initial triangular mesh construction on a single coil for radiative heat transfer. *Arabian Journal for Science and Engineering*, 38(9), 2245-2262.
- Abal Abas, Z. and Salleh, S. (2011). Enhanced Advancing Front Technique with Extension Cases for Initial Triangular Mesh Generation. In *Proceedings of the World Congress on Engineering 2011*.
- Abbasi, T.A. and Abbasi, M.U. (2007). A novel FPGA-based architecture for Sobel edge detection operator. *International Journal of Electronics*, 13(9), pp.889-896.
- Adhikary, N. and Gurumoorthy, B. (2018). A slice-based algorithm for automatic and feature-preserving hole-filling in a CAD mesh model. *Computer-Aided Design and Applications*, 15(6): 780-795.
- Agarwal, V. and Agrawal, N. (2019). Hole Filling Method For Triangular Mesh Generation. *International Journal of Innovative Technology and Exploring Engineering (IJITEE)*, ISSN: 2278-3075, 8(7): 1271-1276.
- Altantsetseg, E., Matsuyama, K., and Konno, K. (2015). Minimum Surface Area Based Complex Hole Filling Algorithm of 3D Mesh. *The Journal of the Society for Art and Science*, 14(2): 26-35.
- Almasi, O.N., and Rouhani, M. (2021). A geometric-based data reduction approach for large low dimensional datasets: Delaunay triangulation in SVM algorithms. *Machine Learning with Applications*, 4, 100025.
- Baker, S., Scharstein, D., Lewis, J.P., Roth, S., Black, M.J., and Szeliski, R. (2011). A database and evaluation methodology for optical flow. *International Journal of Computer Vision*, 92(1): 1-31.
- Barber, C.B., Dobkin, D.P., and Huhdanpaa, H. (1996). The quickhull algorithm for convex hulls. *ACM Transactions on Mathematical Software (TOMS)*, 22(4): 469-483.
- Barbero B.R. and Ureta E. S. (2011), Comparative study of different digitization techniques and their accuracy, *Computer-Aided Design* 43 (2011) 188-206.
- Bello, S. A., Yu, S., Wang, C., Adam, J. M., & Li, J. (2020). Deep learning on 3D point clouds. *Remote Sensing*, 12(11), 1729.
- Belward, J. A., Turner, I. W., & Oqielat, M. A. N. (2009). Numerical investigations of linear least squares methods for derivative estimation. *ANZIAM Journal*, 50, 844-857.

- Beng, N.S. (2015), *Depth Value Approximation of 2D Complex-Shaped Objects for 3D Modelling Using Optical Flow And Trigonometry*, Unpublished PhD Thesis, Universiti Putra Malaysia.
- Berg, M.D., Cheong O., Kreveld M.V. and Overmars M. (2008). *Computational Geometry: Algorithms and Applications*, Springer, Berlin, 2008.
- Bittinger, M. L., Ellenbogen, D.J. and Surgent, S.A. (2012). Mathematical Modeling and Curve Fitting. In *Calculus and Its Applications*, pp.10.Addison-Wesley.
- Biniarz, A. and Dastghaibyfarid, G. (2012). A faster circle-sweep Delaunay triangulation algorithm. *Advances in Engineering Software*, 43(1): 1–13.
- Biniarz, A., Maheshwari, A., and Smid, M. (2015). Higher-order triangular-distance delaunay graphs: Graph-theoretical properties. *Computational Geometry*, 48(9): 646–660.
- Bischoff, S., & Kobbelt, L. (2005, September). Structure preserving CAD model repair. In *Computer Graphics Forum*(Vol. 24, No. 3, pp. 527-536). Oxford, UK and Boston, USA: Blackwell Publishing, Inc.
- Cho, J.H., Song, W., Choi, H., & Kim T. (2017). Hole Filling Method for Depth Image Based Rendering Based on Boundary Decision, *IEEE Signal Processing Letters*, 24(3) ,329-333.
- Cao, M.L, Li, Y.D, Feng, H.Y. and Cai, C. (2019). 3D forest landscape modelling with tilt photography and laser scanning technology [J]. *Journal of Central South University of forestry science and technology*, 39 (12): 10-15.
- Canny, J. (1989). "A computational approach to edge detection". *IEEE Transactions on Pattern Analysis and Machine Intelligence*, PAMI-8(6), pp. 679-698.
- Chen, L. and Holst, M. (2011). Efficient mesh optimization schemes based on optimal Delaunay triangulations. *Computer Methods in Applied Mechanics and Engineering* 200(9–12): 967–984.
- Chen, L., & Xu, J. C. (2004). Optimal delaunay triangulations. *Journal of Computational Mathematics*, 299-308.
- Cheng, S. W. and Jin, J. (2013). Edge flips in surface meshes. *Discrete & Computational Geometry*, 1-42.
- Curless, B. and Levoy, M. (1996, August). A volumetric method for building complex models from range images. In *Proceedings of the 23rd annual conference on Computer graphics and interactive techniques* (pp. 303-312). ACM.

- Davis, J., Marschner, S. R., Garr, M. and Levoy, M. (2002, June). Filling holes in complex surfaces using volumetric diffusion. In *Proceedings. First International Symposium on 3D Data Processing Visualization and Transmission* (pp. 428-441). IEEE.
- Dierckx, P. (1997). On calculating normalized Powell-Sabin B-splines. *Computer Aided Geometric Design*, 15(1), 61-78.
- Dinesh, C., Bajić, I. V. and Cheung, G. (2017, December). Exemplar-based framework for 3D point cloud hole filling. In *2017 IEEE Visual Communications and Image Processing (VCIP)* (pp. 1-4). IEEE.
- Ebrahim M. A. B. (2015). 3D laser scanners' techniques overview. *Int J Sci Res*, 4(10), 323-331.
- Eder, G., Held, M., and Palfrader, P. (2018). Parallelized ear clipping for the triangulation and constrained delaunay triangulation of polygons. *Computational Geometry*, 73, 15–23.
- Farin, G. (1986). Triangular bernstein-bézier patches. *Computer Aided Geometric Design*, 3(2), 83-127.
- Feng, C., Liang, J., Ren, M., Qiao, G., Lu, W. and Liu, S. (2020). A fast hole-filling method for triangular mesh in additive repair. *Applied Sciences*, 10(3), 969.
- Foley, T.A. (1987). Interpolation and approximation of 3-D and 4-D scattered data. *Computers & Mathematics with Applications*, Volume 13(8):711-740.
- Fortune, S. (1987). A sweepline algorithm for Voronoi diagrams. *Algorithmica*, 2(1-4), 153.
- Fortes, M. A., González, P., Palomares, A. and Pasadas, M. (2017). Filling holes with geometric and volumetric constraints. *Computers & Mathematics with Applications*, 74(4): 671-683.
- Freedman, D. (2007). An incremental algorithm for reconstruction of surfaces of arbitrary co-dimension. *Computational Geometry*, 36(2), 106-116.
- Fu, Y., and Wu, T. (2017, October). Research on depth hole filling algorithm based on kinect. In *2017 IEEE International Conference on Signal Processing, Communications and Computing (ICSPCC)* (pp. 1-5). IEEE.
- Gibson, J.J. (1950). *The Perception of the Visual World*, Houghton Mifflin.
- Goodman, T. N. T., Said, H. B., & Chang, L. H. T. (1995). Local derivative estimation for scattered data interpolation. *Applied Mathematics and Computation*, 68(1), 41-50.
- Guo, X., Xiao, J., and Wang, Y. (2018). A survey on algorithms of hole filling in 3D surface reconstruction. *The Visual Computer*, 34(1): 93-103.

- Hansen, H.N., Carneiro, K., Haitjema, H., De Chiffre, L. (2006). Dimensional Micro and Nano Metrology, *CIRP Annals*, 55-2, 721-743.
- Hashim, I., Draman, N. N. C., Karim, S. A. A., Yeo, W. P., & Baleanu, D. (2021). Scattered data interpolation using cubic trigonometric bezier triangular patch. *Computers, Materials and Continua*, 69(1), 221-236.
- Hétroy, F., Rey, S., Andújar, C., Brunet, P. and Vinacua, A. (2011). Mesh repair with user-friendly topology control. *Computer-Aided Design*, 43(1): 101-113.
- Huang, J., Li, W., & Ye, M. (2022). Improved Hole Repairing Method Based on Wavefront Method.
- Iuliano, L., Minetola, P. (2005). Rapid manufacturing of sculptures replicas: A comparison between 3d optical scanners. *CIPA 2005 XX International Symposium*, 26 September – 01 October, 2005, Torino, Italy.
- Jiang, Y., Liu, Y. T., and Zhang, F. (2010, April). An efficient algorithm for constructing Delaunay triangulation. In *Information Management and Engineering (ICIME), 2010 The 2nd IEEE International Conference on* (pp. 600-63). IEEE.
- Jianyuan, Y. (2008). Study on edge detection algorithm in image processing. *Science and technology information*, 4, 67-68.
- Ju, T. (2009). Fixing geometric errors on polygonal models: a survey. *Journal of Computer Science and Technology*, 24(1): 19-29.
- Ju, T. (2004, August). Robust repair of polygonal models. In *ACM Transactions on Graphics (TOG)*, Vol. 23, No. 3, pp. 888-895, ACM.
- Ju, T., Losasso, F., Schaefer, S., & Warren, J. (2002, July). Dual contouring of hermite data. In *ACM transactions on graphics (TOG)* ,Vol. 21, No. 3, pp. 339-346, ACM.
- Karim, S. A. A., Saaban, A., & Nguyen, V. T. (2020). Scattered data interpolation using quartic triangular patch for shape-preserving interpolation and comparison with mesh-free methods. *Symmetry*, 12(7), 1071.
- Kazi, A., Saasthanmath, A., Meena, S. M., Gurlahosur, S. V., & Kulkarni, U. (2020). Detection of holes in 3D architectural models using shape classification based Bubblegum algorithm. *Procedia Computer Science*, 167, 1684-1695.
- Kong, V. P., Ong, B. H., & Saw, K. H. (2004). Range restricted interpolation using cubic Bézier triangles.
- Lamnii, A., Lamnii, M., & Mraoui, H. (2015). A normalized basis for condensed C1 Powell–Sabin-12 splines. *Computer Aided Geometric Design*, 34, 5-20.

- Lawson, C. L. (1977). *Software for C1 surface interpolation. Mathematical Software III.*
- Liao, B., Hu, J., & Gilmore, R. O. (2021). Optical flow estimation combining with illumination adjustment and edge refinement in livestock UAV videos, *Computers and Electronics in Agriculture*, 180, 105910.
- Lin, S. C., Shih, T. K., and Hsu, H. H. (2017, August). Filling holes in 3D scanned model base on 2D image inpainting. In *2017 10th International Conference on Ubi-media Computing and Workshops (Ubi-Media)*, pp. 1-6, IEEE.
- Liu, Z., Bai, L., and Miao, Y. (2015, January). A Novel Surface Completion Method. In *International Conference on Education, Management, Commerce and Society (EMCS-15)*. Atlantis Press.
- Liu, Y. and Zhang, H. (2017). A Hole-filling method based on fuzzy inference. *International Journal of Urban Design for Ubiquitous Computing*, 5(1): 21-26.
- Luo, G., Zhu, Y. and Guo, B. (2017). Fast MRF-based hole filling for view synthesis. *IEEE Signal Processing Letters*, 25(1): 75-79.
- Medeiros, E., Velho, L. and Lopes, H. (2003). A topological framework for advancing front triangulation. In *Computer Graphics and Image Processing, 2003. SIBGRAPI 2003, XVI Brazilian Symposium on IEEE*, October, pp. 45-51.
- Ngo, H.T.M. and Lee, W.S. (2011). Feature-first hole filling strategy for 3D meshes. In *International Conference on Computer Vision, Imaging and Computer Graphics*, Springer, Berlin, Heidelberg, March, 53-68.
- Nooruddin, F. S. and Turk, G. (2003). Simplification and repair of polygonal models using volumetric techniques. *IEEE Transactions on Visualization and Computer Graphics*, 9(2): 191-205.
- Ooi, Y., Chang, L. H. T., Wong, Y. P., & Piah, A. R. M. (2004, July). A choice of weights for convex combination methods in estimating partial derivatives. 233-236.
- Osherovich, E., and Bruckstein, A. M. (2008). All triangulations are reachable via sequences of edge-flips: an elementary proof. *Computer Aided Geometric Design*, 25(3): 157-161.
- Oqielat, M. N., Turner, I. W., & Belward, J. A. (2009). A hybrid Clough-Tocher method for surface fitting with application to leaf data. *Applied Mathematical Modelling*, 33(6), 2582-2595.
- Percell, P. (1976). On cubic and quartic Clough-Tocher finite elements. *SIAM Journal on Numerical Analysis*, 13(1), 100-103.

- Perumal, L. (2019). New approaches for Delaunay triangulation and optimisation. *Heliyon*, 5(8).
- Podolak, J. and Rusinkiewicz, S. (2005). Example based 3d scan completion, in *SGP'05: Proceedings of the Third Eurographics Symposium on Geometry Processing*, pp.23–32.
- Qian, Y., Xinhua, L., & Xianhui, G. (2010, July). New method of partial derivatives estimation based on convex combination. In *Industrial and Information Systems (IIS), 2010 2nd International Conference on* (Vol. 1, pp. 49-52). IEEE.
- Rao, S. and Wang, H. (2021). Robust optical flow estimation via edge preserving filtering. *Signal Processing: Image Communication*, 96, 116309.
- Renka, R.J. and Cline, A. K. (1984). A triangle-based C1 interpolation method. *Rocky Mountain J. Math*, 14(1).
- Rianmora, S. and Rangsiyangkoon, M. (2017). Alternative Optical Acquisition Technique for Supporting Reverse Engineering Process. *Int. J. Mater. Mech. Manuf*, 5, 286-289.
- Saaban, A., Piah, A. R. M., & Majid, A. A. (2006, July). Positivity-Preserving Scattered Data Interpolating Surface using C^1 Piecewise Cubic Triangular Patches. In *Computer Graphics, Imaging and Visualisation, 2006 International Conference on* (pp. 490-495). IEEE.
- Saaban, A., Piah, A. R. M., & Majid, A. A. (2007, August). Range restricted $C2$ interpolant to scattered data. In *Computer Graphics, Imaging and Visualisation, 2007. CGIV'07* (pp. 183-188). IEEE.
- Saaban, A., Majid, A. A., & Piah, R. M. (2009). Visualization of rainfall data distribution using quintic triangular Bezier patches. *Bulletin of the Malaysian Mathematical Sciences Society*, 32(2).
- Saaban, A., Ahmad, N., Hassan, M. H., Mansor, K. H., Mohamad, M. S. A., Alipiah, F. M. & Khalid K. (2012). Scattered data interpolation using combination method of triangular patches. *Monographs of Applied Mathematics*.
- Schumaker, L. L., & Speleers, H. (2010). Nonnegativity preserving macro-element interpolation of scattered data. *Computer Aided Geometric Design*, 27(3), 245-261.
- Schilling, A., Bidmon, K., Sommer, O. and Ertl, T. (2008). Filling arbitrary holes in finite element models. In *Proceedings of the 17th International Meshing Roundtable* (pp. 231-248). Springer, Berlin, Heidelberg.
- Sing CC (2008), Automatic Mesh Repair and Optimization for Quality Mesh Generation (Doctoral dissertation).

- Shewchuk, J. R. (2012). Unstructured mesh generation. *Combinatorial Scientific Computing*, 12(257), 2.
- Sheng, B., Zhao, F., Yin, X., Zhang, C., Wang, H., Huang, P. (2018). A Lightweight Surface Reconstruction Method for Online 3D Scanning Point Cloud Data Oriented toward 3D Printing. *Math. Probl. Eng.* 2018, 1–16.
- Soni, A. and Rai, A. (2021, January). CT Scan Based Brain Tumor Recognition and Extraction using Prewitt and Morphological Dilation. In *2021 International Conference on Computer Communication and Informatics (ICCCI)* (pp. 1-6). IEEE.
- Speleers, H. (2010a). A normalized basis for reduced Clough–Tocher splines. *Computer Aided Geometric Design*, 27(9), 700-712.
- Speleers, H. (2015a). A new B-spline representation for cubic splines over Powell–Sabin triangulations. *Computer Aided Geometric Design*, 37, 42-56.
- Speleers, H. (2010b). A normalized basis for quintic Powell–Sabin splines. *Computer Aided Geometric Design*, 27(6), 438-457.
- Speleers, H. (2015b). A family of smooth quasi-interpolants defined over Powell–Sabin triangulations. *Constructive Approximation*, 41(2), 297-324.
- Su, P. and Drysdale, R. L. S. (1997). A comparison of sequential delaunay triangulation algorithms. *Computational Geometry*, 7(5–6), 361–385.
- Tabib, R. A., Jadhav, Y. V., Tegginkeri, S., Gani, K., Desai, C., Patil, U. and Mudenagudi, U. (2020). Learning-Based Hole Detection in 3D Point Cloud Towards Hole Filling. *Procedia Computer Science*, 171, 475-482.
- Tang, Q., & Ren, Y. (2020). Preliminary Discussion on the Refinement Mesh Generation for Adaptive Analysis. *Journal of Applied Mathematics and Physics*, 8(8), 1560-1567.
- Tekumalla, L. S. and Cohen, E. (2004). A hole-filling algorithm for triangular meshes. *School of Computing, University of Utah, UUCS-04-019, UT, USA*, 2.
- Tingjiao L., Zhenjiang C., Wendi W. (2011). Edge Extraction of Cow's Digital Image Based on MATLAB[J]. *Journal of Agricultural Mechanization Research*. 2011, 2(2):23-26.
- Tóth, T., & Živčák, J. (2014). A comparison of the outputs of 3D scanners. *Procedia Engineering*, 69, 393-401.
- Wang Q., Yang P., Jiang Y., Huang L., and Zhang G. (2016, August). A Topology Structure Repair Algorithm for Triangular Mesh Model. In *Embedded Software and Systems (ICESSE), 2016 13th International Conference on* (pp. 131-136). IEEE.

- Wang, C. W., Yang, T. C., Chiang, S. H. and Wang, T. (2017, December). Identifying and filling occlusion holes on planar surfaces for 3-D scene editing. In *2017 Asia-Pacific Signal and Information Processing Association Annual Summit and Conference (APSIPA ASC)* (pp. 251-254). IEEE.
- Wang, X., Liu, X., Lu, L., Li, B., Cao, J., Yin, B. and Shi, X. (2012), Automatic hole-filling of CAD models with feature-preserving, *Computers & Graphics*, 36(2): 101-110.
- Wang, W., Su, T., Liu, H., Li, X., Jia, Z., Zhou, L., Song, Z. and Ding, M. (2019). Surface reconstruction from unoriented point clouds by a new triangle selection strategy. *Comput. Graph.* 84, 144-159.
- Wang, X., Cao, J., Liu, X. and Li, B. (2011). Advancing front method in triangular meshes hole-filling application, *Journal of Computer-Aided Design and Computer Graphics*, 23(6):1048-1054.
- Whelan, T. (1986). A representation of a C2 interpolant over triangles. *Computer Aided Geometric Design*, 3, 53-66.
- Weckenmann A., Peggs G., Hoffmann J., 2006. Probing systems for dimensional micro- and nano-metrology, *Meas. Sci. Technol.* 17, 504–509.
- Wei, W. E. I. (2011). Comparative study on some common edge detection methods based on Matlab. *Modern Electronics Technique*, 34(4), 91-94.
- Wu, B. and Wang, S. (2005). Automatic triangulation over three-dimensional parametric surfaces based on advancing front method. *Finite elements in analysis and design*, 41(9-10): 892-910.
- Xia, C. and Zhang, H. (2017). A fast and automatic hole-filling method based on feature line recovery. *Computer-Aided Design and Applications*, 14(6): 751-759.
- Xu X.L. (2008) , Application of matlab in digital image processing, *Modern Computer*, 43(5), pp. 35-37.
- Xu, B., Li, Z. and Tan, Y. (2013). Feature based hole filling algorithm on triangular mes. In *International Conference on Computer and Computing Technologies in Agriculture*. Springer, Berlin, Heidelberg, September, 90-101.
- Zalik, B. (2005). An efficient sweep-line Delaunay triangulation algorithm. *Computer-Aided Design*, 37(10): 1027-1038.
- Zhao, W., Gao, S. and Lin, H. (2007). A robust hole-filling algorithm for triangular mesh. *The Visual Computer*, 23(12): 987-997.
- Zhou, Z. (2018). Application of 3D laser scanning technology in deformation monitoring of Baoyang pumped storage power junction [J]. *Hydropower*, 44 (10): 75-77.